



Continuum Control Corporation

Self-Powered™ Piezoelectric Active Vibration Suppression

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Sponsor: DARPA

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Continuum Control Corporation

Mission

- Develop and manufacture integrated devices & systems for sensing and control using Smart Materials

Current Focus Areas

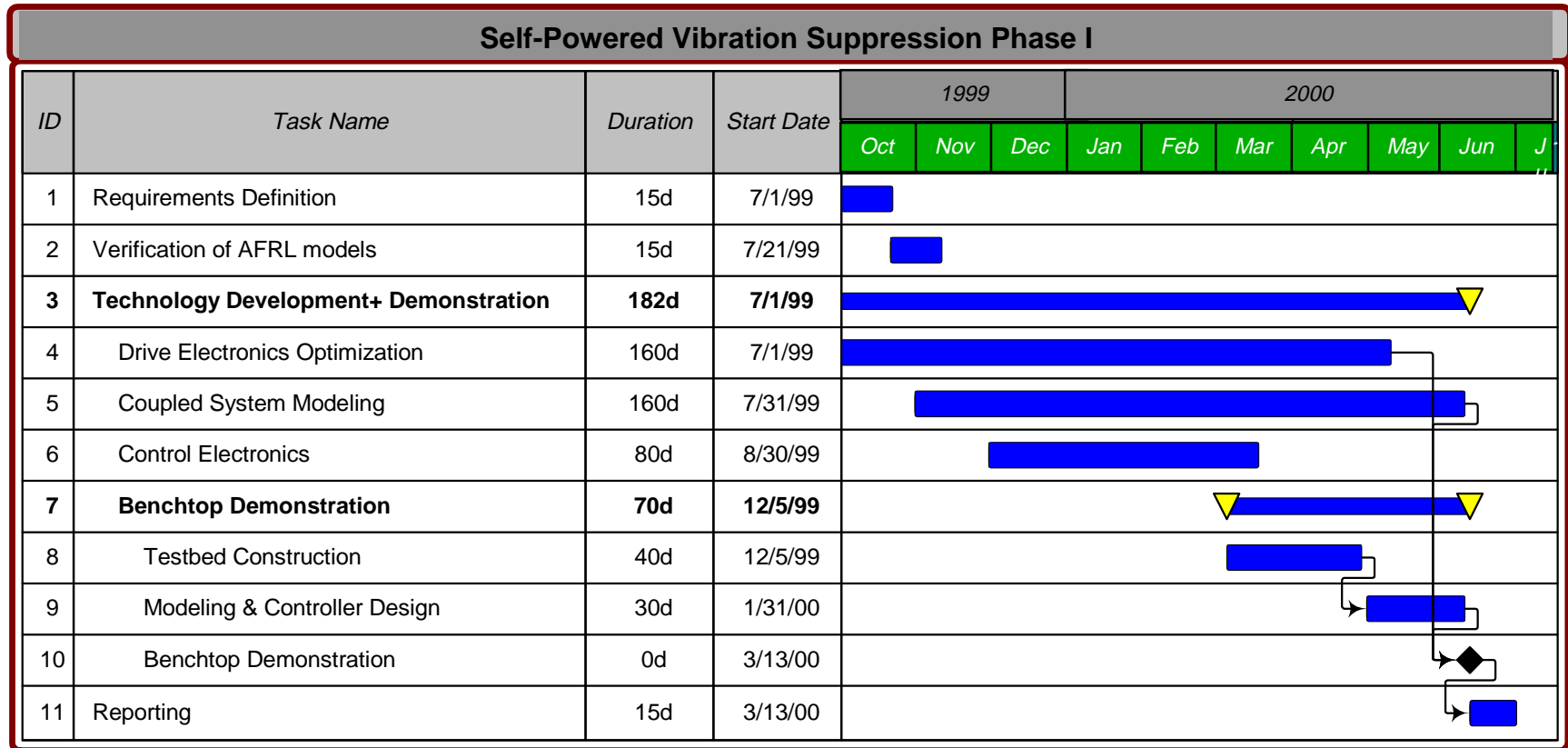
- Active Fiber Composites, Single Crystal AFCs
- High Efficiency Electronics, Self-Powered Damping Systems
- Integrated Devices, Energy Harvesting

Status

- Founded July 1998
- Both government R&D and commercial programs



Schedule



Self-Powered™ Vibration Suppression Program

2 Year DARPA funded program (*Dr. E. Garcia*)

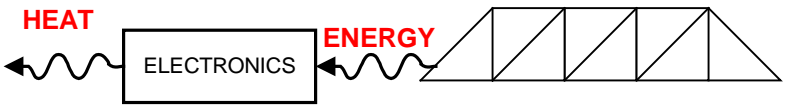
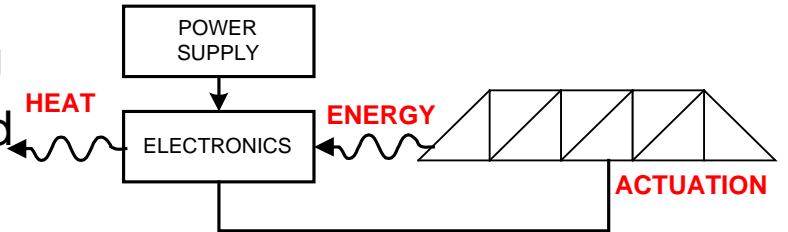
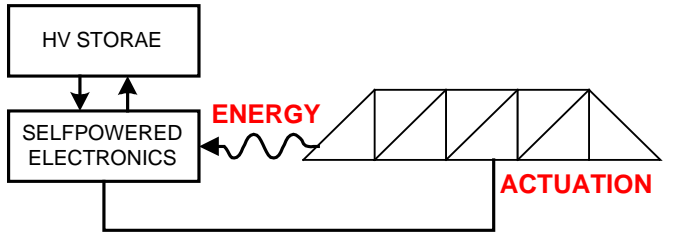
Primary Objective:

Design and demonstrate vibration reduction using novel self-powered™ piezoelectric devices and electronics

Technical Program Goals:

- Systems approach: develop tools for integrated systems level analysis of structure, piezoelectrics, and electronics
- Electronics Focus: investigate circuit designs for improved performance
- Experimental Demonstration: explore range of achievable performance

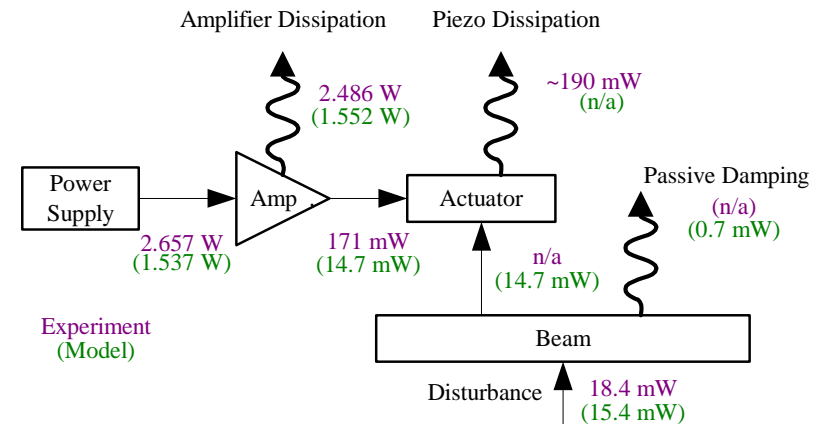
Possible Vibration Suppression Systems

Concept	Characteristics
Passive <ul style="list-style-type: none">Vibration is reduced by dissipating energy as heat	<ul style="list-style-type: none">simple electronicslow damping 
Active (Powered) <ul style="list-style-type: none">Externally powered actuators reduce vibration	<ul style="list-style-type: none">10-100x dampingEnergy dissipated in electronics 
Self-Powered™ <ul style="list-style-type: none">Actuators reduce vibration using power from structure	<ul style="list-style-type: none">10-100x dampingNo external power 

Linear vs. Switching Amplifier

Existing Active damping system

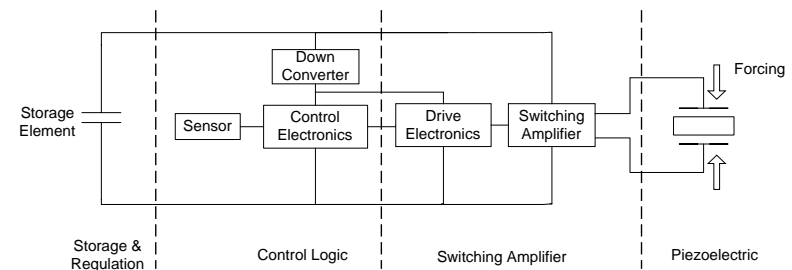
- Linear amplifiers
- Poor efficiency, energy wasted as heat
- Require external power



Power dissipation in a linear amplifier [Warkentin, MIT, 1995]

Self-Powered™ damping system

- Use switching amplifier and High Voltage storage elements.
- Energy is harvested from the vibration environment, and used to power actuators for damping.
- No external power required.
- Superior damping to passive piezoelectric shunts.



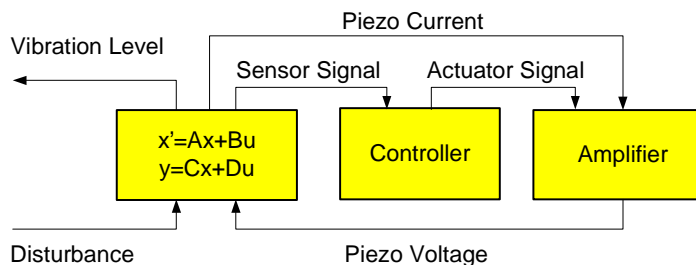
Modeling Approach

Analytical Modeling

- Restricted to analysis of simple circuits.
- Yields closed form expressions, useful for understanding important trends.

Simulink (Matlab) Simulations

- Allow realistic modeling of more complex nonlinear electronic circuits
- Integrated modeling of structural dynamics, piezoelectric, and electronics.
- Use Simulink model for comparison of different system topologies and parametric studies.

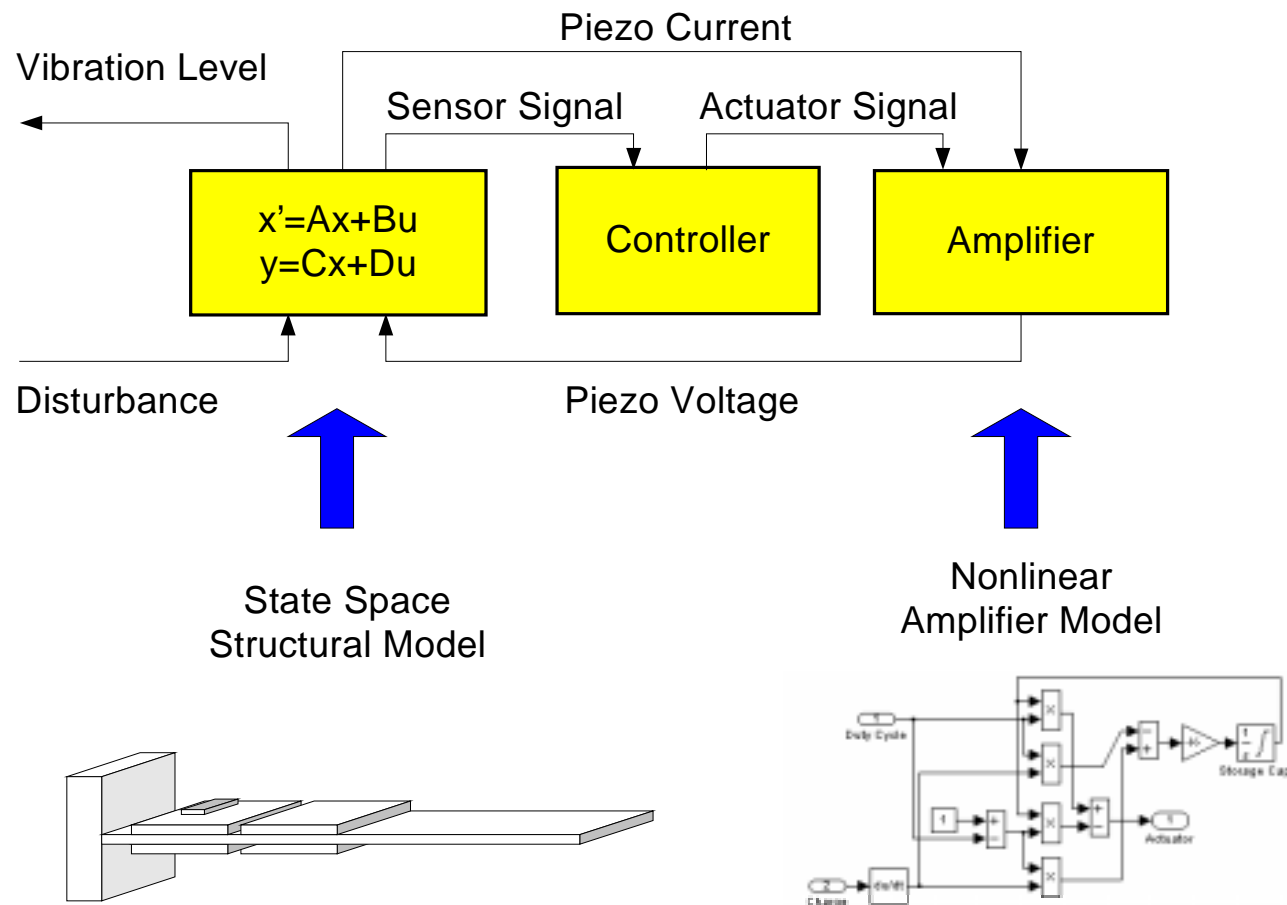


SPICE Simulations

- Accurate modeling and design of the actual electronic circuits

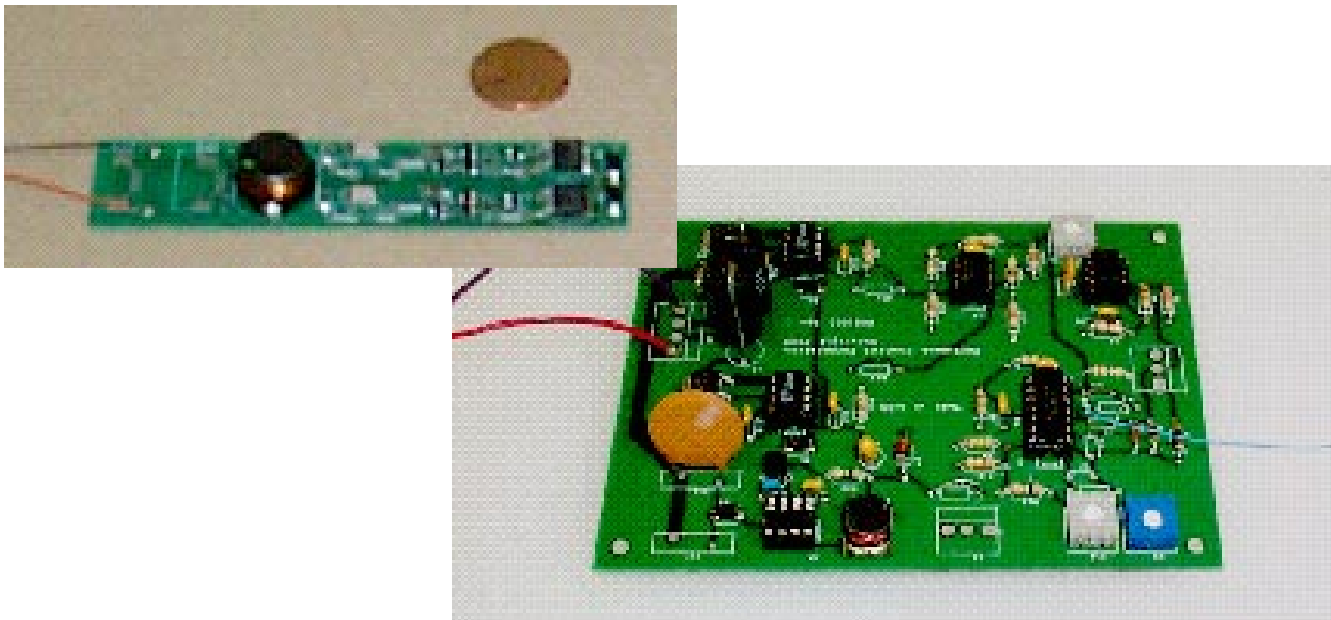
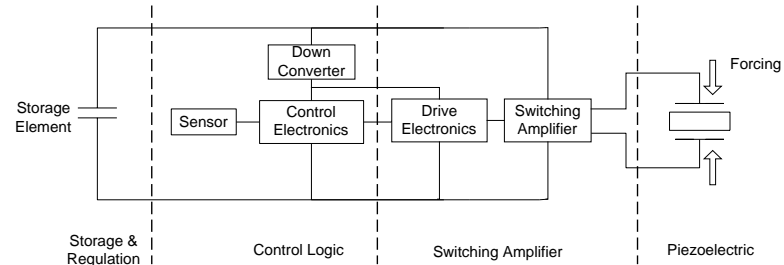
Coupled System Modeling

- Synergistic design of Structure, Control System, and Amplifier electronics
➡ higher performance / lower power



Electronics Development

- Several generations of self-powered™ circuits have been implemented.
- Latest circuit designed for 600V.
- Good correlation between SPICE simulations and circuit performance.



Laboratory Demonstration Testbed

Structure

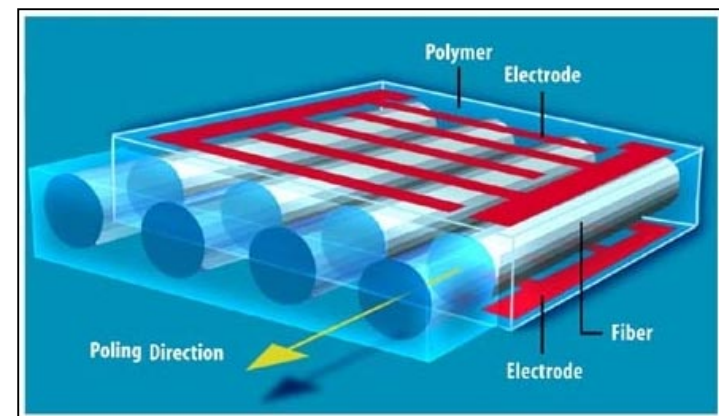
- 6"x12" cantilevered fiberglass plate
- 4 **Active Fiber Composite (AFC)** Actuators (2"x5" each)
- First Mode: 9Hz

Disturbance Source

- Ling Dynamic System V408 Shaker (22lbf)

Active Fiber Composite Actuators

- High Performance, Conformable, Robust, Directional
- **twice the strain energy density of 3-1 mode monolithic piezoceramics**



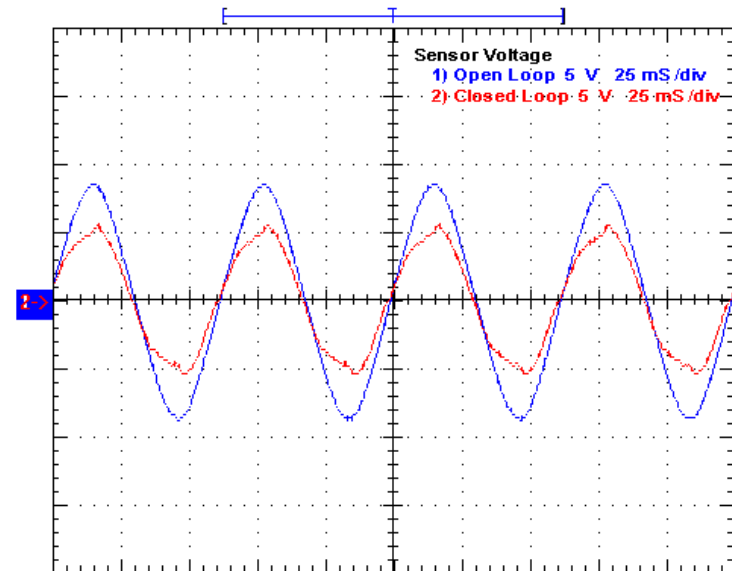
Experimental Demonstration

Operation

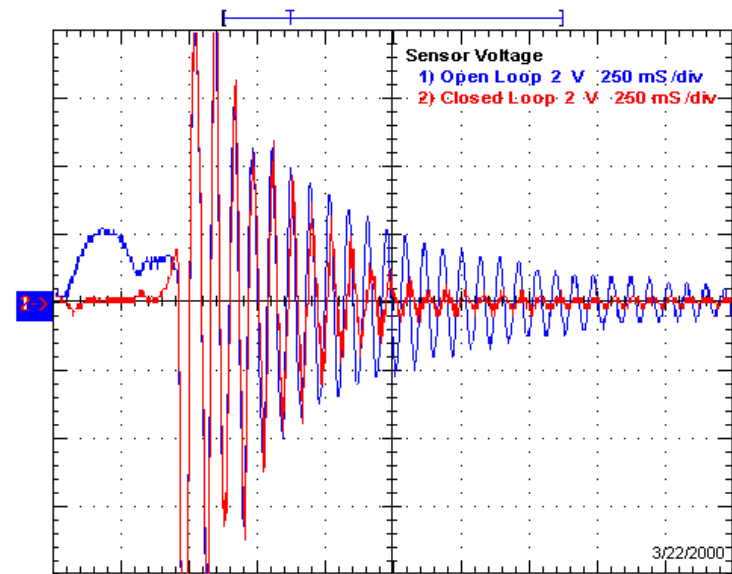
- Self-powered™ switching electronics amplify and phase shift piezo voltage to produce damping

Results

- No external HV power required. The vibration of structure charges storage capacitor to as high as 500V.
- Increased damping observed with self-powered™ damping module, in both steady state and transient operation.



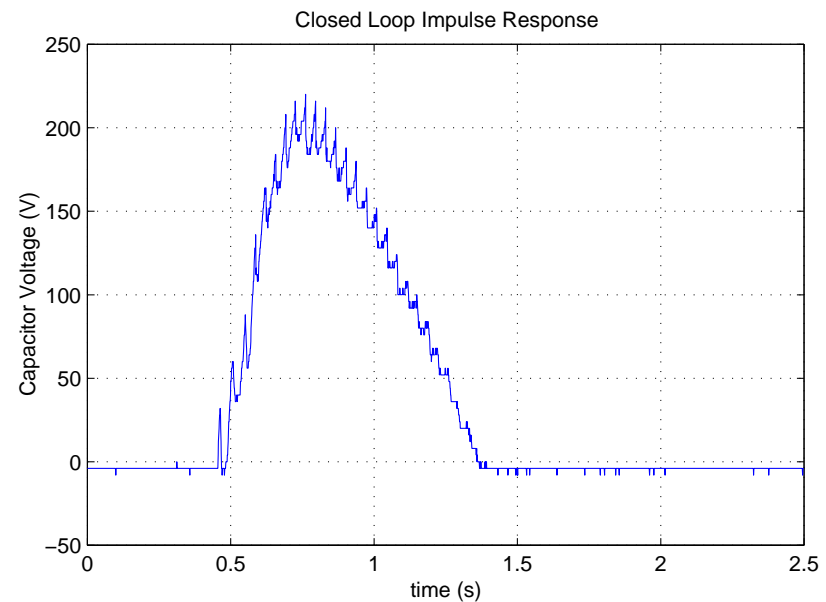
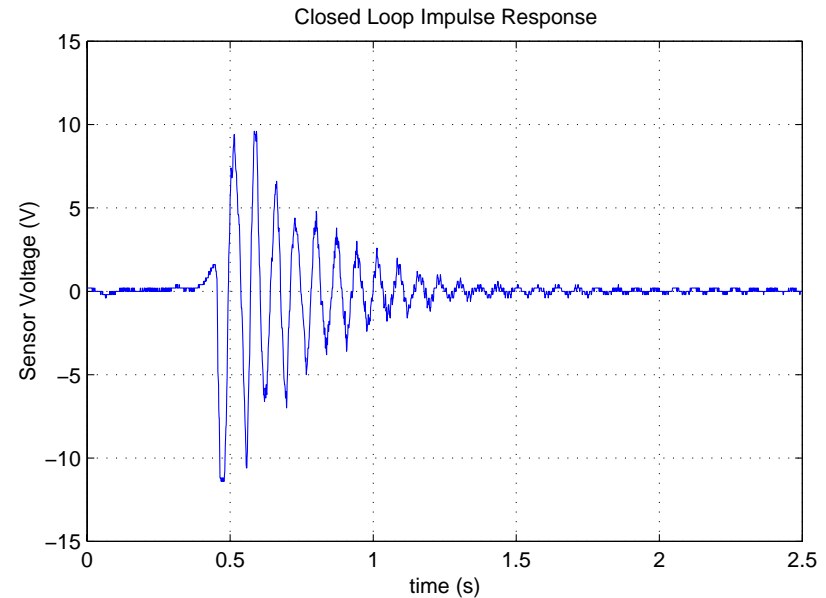
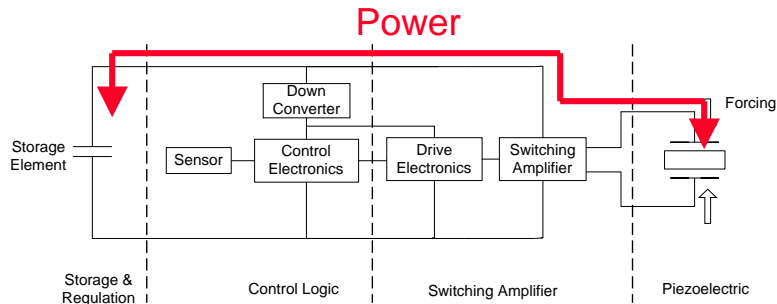
Steady State Response



Transient Response

Self-Powered™ High Voltage Supply

- Switching Amplifier allows bi-directional power flow
- high voltage storage element is charged up using power extracted from piezoelectric actuators
- Storage element can power actuators



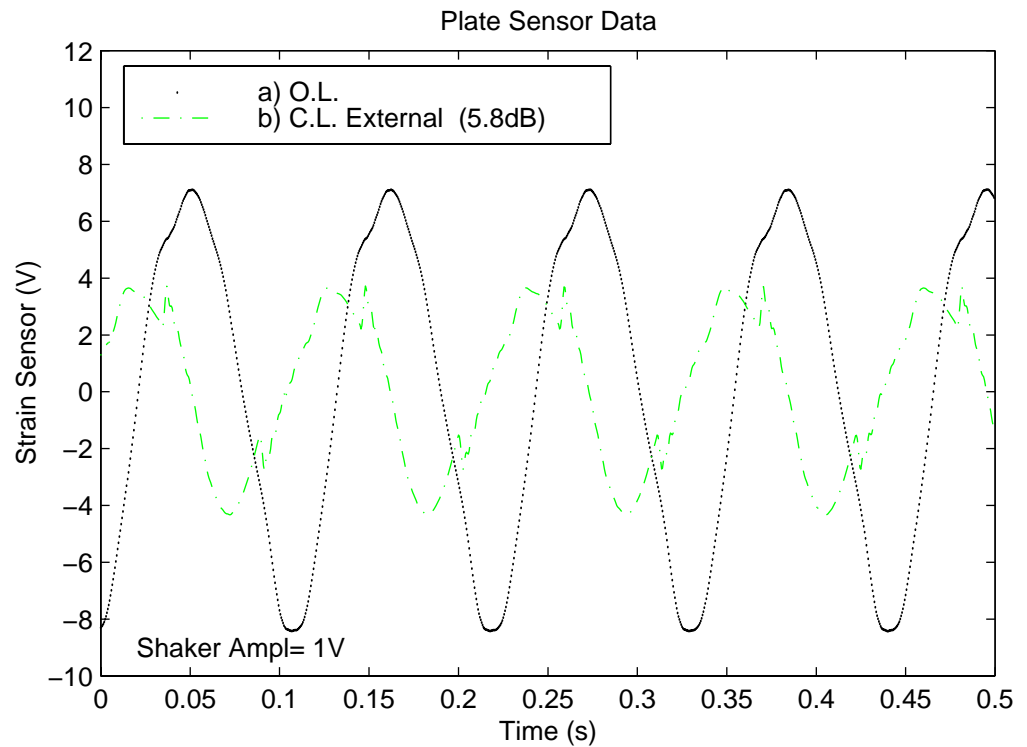
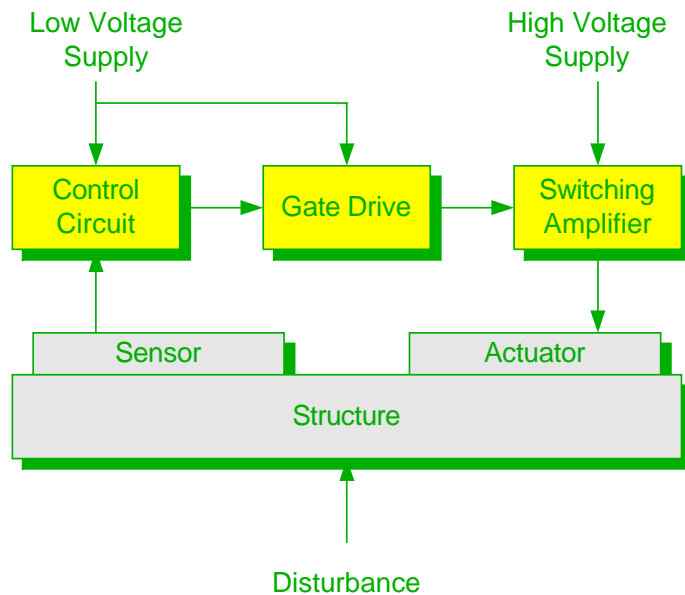
Experimental Data – Externally Powered Active Damping

System

- Proprietary switching amplifier with external power supply
- Proprietary control algorithm

Results

- Closed Loop reduction in vibration amplitude: **5.8dB**



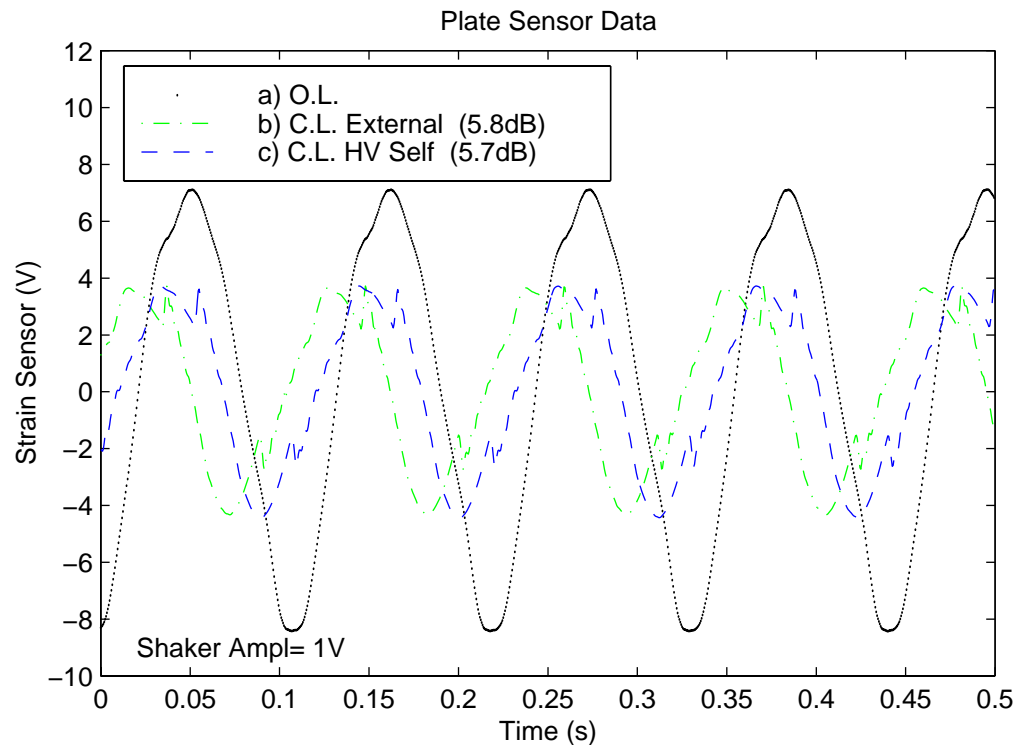
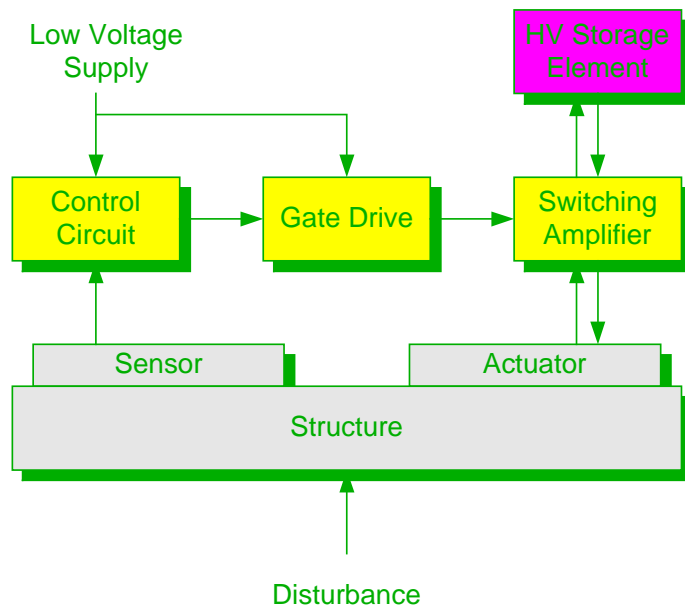
Experimental Data – Self-Powered™ Active Damping I

System

- Proprietary switching amplifier with self-powered™ High Voltage supply
- Proprietary control algorithm

Results

- Closed Loop reduction in vibration amplitude: **5.7dB**



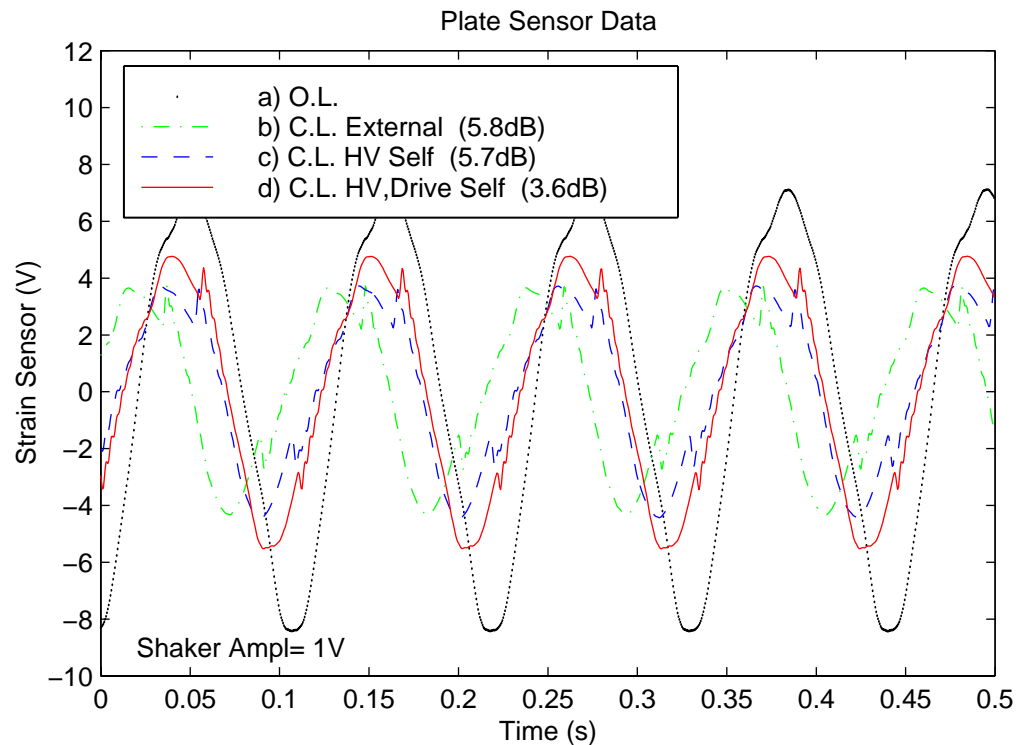
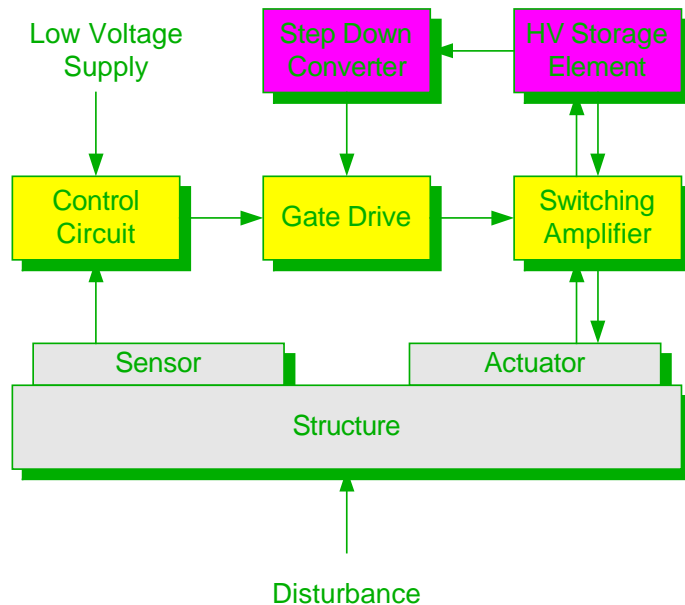
Experimental Data – Self-Powered™ Active Damping II

System

- Proprietary switching amplifier with self-powered™ high voltage supply
- Step-down converter for powering low voltage electronics

Results

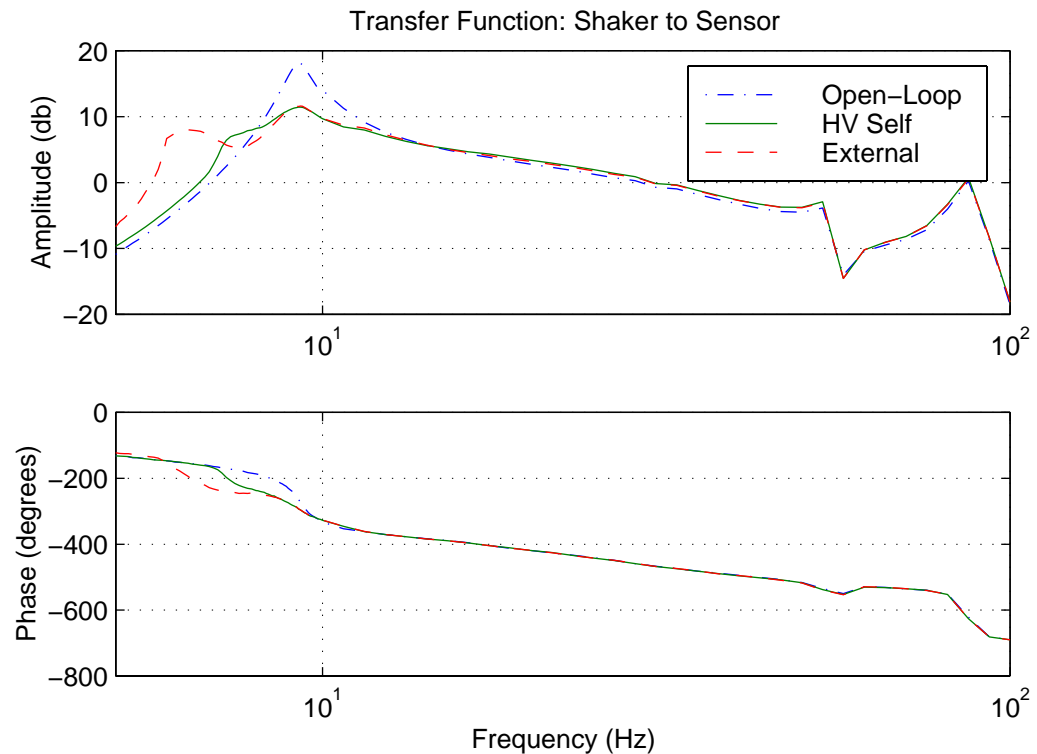
- Closed loop reduction in vibration amplitude: **3.6db**



Experimental Frequency Response Data

- Self-powered™ and externally powered systems have comparable performance at design frequency.
- Off design frequency, externally powered control system may actually increase vibration level.
- Lack of external energy source means Self-powered™ system can not suffer from *gain instability*.
- Fertile ground for further control development

Due to the high system nonlinearity, frequency response data is dependent on signal amplitude



Results Summary

- Developed fully integrated structural/electrical numerical models of Self-Powered™ Damping system
- Successfully demonstrated Self-Powered™ Vibration Suppression System experimentally.
- Increased damping observed with Self-powered™ damping module, in both steady state and transient operation.
- No external High Voltage power required. The vibration of structure charges storage capacitor to as high as 500V.
- Performance of Self-powered™ system comparable to an externally powered control system in damping persistent vibrations.
- Initial implementation of step-down converter for powering the entire control circuit

Future Work

Electronics optimization

- Reduce power requirements of the sensor/control electronics
- Reduce inefficiencies in the switching amplifier electronics

Design for more complex disturbance sources

- White noise vibration environment
- More sophisticated control algorithms

Development of Self-Powered™ Vibration Suppression Patch

- Design/Integration of Actuator and Self-Powered™ electronics into a self contained patch
- Prototype manufacturing and testing

Feasibility study for full scale system

Future Circuit Improvements

The components required for Self-powered™ damping circuitry have several stringent requirements.

- MOSFET requirements:
 - High voltage, low current.
 - Available HV MOSFETs are designed for high power/current.
- Inductor requirements:
 - High inductance, high voltage, low current.
 - Available inductors are design for:
 - Switching power supplies (high voltage/current, but relatively low inductance).
 - RF applications (high inductance, but low voltage/current).